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EX LUPI: HISTORY AND SPECTROSCOPY

G. H. HERBIG
Institute for Astronomy, University of Hawaii, Honolulu, HI 96822, USA
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ABSTRACT

EX Lupi is the prototype of the "EXor" class, which are pre-main-sequence variables that normally remain at minimum light, but are subject to relatively brief (a few months to a few years) flare-ups of several magnitudes amplitude. This paper examines what is known about EX Lup itself, and describes new photometric and spectroscopic information collected between 1995 and 2005, during which time the star underwent four flare-ups. It is concluded, in agreement with previous investigations, that the flare-ups are due to intermittent mass infall. The evidence: veiling of the M0-type absorption spectrum, appearance of reversed P Cyg–type absorption components displaced up to +340 km s^{-1} at many emission lines, and striking variations in emission-line structure. It remains to be seen whether these phenomena are shared by other EXors, which are often classified as such on the basis of fragmentary observational evidence.

Key words: stars: activity — stars: evolution — stars: individual (EX Lupi) — stars: pre–main-sequence

1. INTRODUCTION

There are two generally recognized types of pre-main-sequence stars that are subject to major increases in brightness: FUors and EXors (sometimes called "subfuors"), named after the prototypes FU Orionis and EX Lupi.

FUor characteristics are better defined: they exhibit (as far as our experience extends) a single major increase in brightness (>4–5 mag), following which they show a complex absorption spectrum much like that of a F- or G-type high-luminosity star of significant $v_{eq} \sin i$, a powerful shortward-shifted P Cyg–like absorption component at Hα, and a strong Li I λ6707 absorption line. These characteristics are common to the best-observed members of the class: FU Ori, V1057 Cyg, and V1515 Cyg. A number of secondary properties are not unique to the FUor class, such as association with an arc-shaped reflection nebula and possession of strong CO 2 μm absorption bands. Some aspects of the FUor problem have recently been discussed by Herbig et al. (2003) and Hartmann et al. (2004).

EXors are not so neatly pigeonholed. The original list of candidates (Herbig 1989) was simply a list of variables that exhibited large-range outbursts and displayed spectra like those of T Tauri stars (TTSs) at maximum light. At that time, only fragmentary information was available for some of these objects, so the defining characteristics of the class came, by default, to be dominated by what was known of the prototype, namely, that the outbursts of EX Lup are repetitive, its spectrum does not show the shortward-displaced outflow signature at Hα so striking in FUors, Li I λ6707 is prominent, and at minimum it is an M-type dwarf of modest $v_{eq} \sin i$. But that original list also included active classical TTSs (CTTSs) such as DR Tau, which are variable on both short and long timescales and are clearly are not quiescent between occasional flare-ups, and so are not EXors in the sense of those criteria. It remains to be determined how many stars actually behave like EX Lup, and whether they can be recognized spectroscopically.

A considerable amount of observational information has been accumulated about stars on that original list of EXor candidates, but first it is desirable to review what is now known of EX Lup itself, particularly in light of new spectroscopy described here.

2. EX LUPI

More is known now about the photometric behavior of EX Lup[1] than was the case in 1989. From the 1893–1941 photographic study of EX Lup by McLaughlin (1946) it had appeared "that the variations were irregular and that the star sometimes remained inactive at minimum light (about $B = 14.7$) for years at a time but that it occasionally brightened at least 2.5 mag to 'nova-like maxima,' which were followed by smaller irregular fluctuations for 1–2 yr" (Herbig et al. 2001, p. 1547). Subsequent coverage by the visual observers of the Royal Astronomical Society of New Zealand reinforced the impression that the characteristic pattern is of sporadic flare-ups from minimum light, by as much as 4 mag on one occasion, although it sometimes remains at an intermediate level for extended periods. EX Lup underwent a period of mild activity in 1993–1994, and on that occasion was observed both photometrically and spectroscopically in some detail (Herbig et al. 2001, where the early history is collected; Lehmann et al. 1995; Patten 1994).

2.1. *The 1998 Outburst*

Figure 1 shows the light curve of EX Lup in 1995–2005, constructed entirely from visual observations made between 1995 and 2005 by A. F. Jones of Nelson, New Zealand, to whom we are much indebted for making this material available. The coverage is of course not complete for seasonal reasons, but one sees that during that period there were at least four outbursts: in 1995 April to $m_{vis} = 11.5$, in 1998 June to $m_{vis} = 11.3$, in 1999 June–July to $m_{vis} = 11.1$, and in 2002 July–August to $m_{vis} = 10.8$.

Spectroscopic observations with the HIRES spectrograph at the Keck I telescope[2] began on the occasion of the 1998 flare-up. On June 22 we were notified by A. F. Jones that EX Lup, normally at about $m_{vis} = 12.6$–12.9, had brightened to 11.4 mag sometime between May 31 and June 18. Fortunately, A. Boesgaard

[1] $\alpha = 16^h03^m05.49^s$, $\delta = -40°18'25.3''$ (J2000.0), $l, b = 337.9°, +09.2°$.
[2] The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

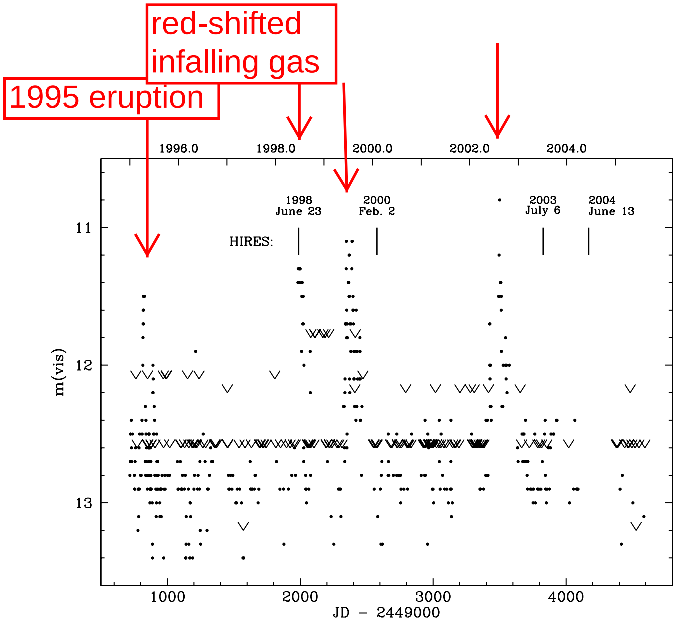

FIG. 1.—Light curve of EX Lupi between 1995 and 2005, from visual estimates by A. F. Jones. The carets indicate that the star was fainter than that value on that occasion. The dates when Keck HIRES spectrograms were obtained are marked along the top.

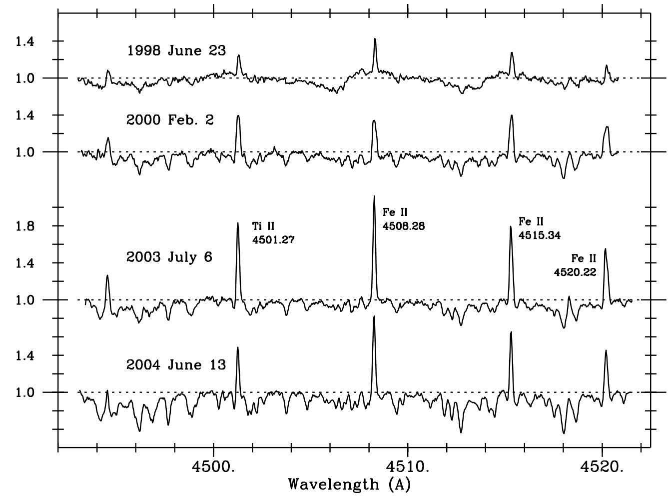

FIG. 2.—The 4493–4520 Å region in EX Lup on the dates indicated, from the HIRES spectrograms, all plotted at the same vertical scale and normalized to the continuum. The top spectrum is the mean of five individual exposures obtained near maximum light; the longward absorption components are apparent, but are confused by M-type structure, which becomes more prominent when the star is fainter.

was working with HIRES on another program, so she was able to obtain a series of six spectrograms of EX Lup between June 23.31 and 23.41 (UT). The absorption spectrum of EX Lup at minimum light is known to be about M0 V (Herbig 1977), so HIRES spectrograms of HD 147379, type M1 V, and of BD +10 3724, type K7 V, were obtained then and later with the same equipment to serve as reference. Those spectrograms, of resolution about 48,000, cover the range 4450–6900 Å, with some interorder gaps. Subsequent HIRES observations were obtained in 2000, 2003, and 2004, when the star was fainter, and are discussed in § 2.2. The dates of all observations are given in Table 1, together with the m_{vis} magnitude at the time, and are indicated on the light curve of Figure 1. Figure 2 shows how the spectrum in the 4500 Å region changed during these HIRES observations. The spectra are normalized to the continuum level and plotted on the same vertical scale.

There have been no previous high-resolution observations of EX Lup, except for the Hα profile published by Reipurth et al. (1996). The medium-resolution spectroscopy by Herbig and Patten was described in Herbig et al. (2001). Spectra at similar resolution were published by Lehmann et al. (1995), but these were obtained both when the star was bright ($V \approx 12.0$) during the 1994 March maximum, and 5 months later, when the star was at about $V = 13.0$. They demonstrated that at maximum the star had become much bluer due to the addition of a hot continuum, and that longward "reversed P Cygni" absorption components had appeared at Hβ and the higher Balmer lines. At those resolutions, the main evidence of the continued presence of a late-type contribution is the depression near 4800 Å due to MgH.

TABLE 1

HIRES OBSERVATIONS OF EX LUPI

Date (UT)	m_{vis}	W(Hα) (Å)	W(Hβ) (Å)	$v_{\odot}$(M Star) (km s^{-1})
1998 Jun 23.3	11.3	50:[a]	12[b]	+0.2 ± 0.3
2000 Feb 2.64	13.1:	22	16	+0.5 ± 0.4
2003 Jul 6.26	12.7	52	22	−0.1 ± 0.2
2004 Jun 13.54	. . .	40	17	+0.2 ± 0.3

[a] Hα emission was partly off the edge of the order, so the number given is twice the W value of the longward half of the line.

[b] The longward absorption component is not included in the value given.

The Keck spectra of EX Lup during the 1998 maximum showed that phenomenon in much greater detail. The late-type absorption spectrum was very evident, but it was diluted by a blue continuum 5–6 times brighter at 4500 Å. A large number of narrow, slightly asymmetric emission lines of He I, He II, Fe II, Fe I, Ti II, Mg II, Cr II, and Si II were present. Notably, the [S II] lines at 6716 and 6730 Å, which are considered an outflow signature, were not detected on this or on subsequent HIRES spectra. The stronger Fe II and Ti II lines were clearly composite: the narrow component at the stellar velocity was superposed on a broader line displaced 10–20 km s^{-1} shortward. That structure has been observed in active TTSs, and these were dubbed the narrow component (NC) and the broad component (BC) (Hamann & Persson 1992; Beristain et al. 1998).

In that spirit, Figure 3 illustrates how Fe II λ5018 can be decomposed into two Gaussians. In this case, the BC has a FWHM of 140 km s^{-1} and an equivalent width (W) of 1.12 Å, while the FWHM and W of the NC are 23 km s^{-1} and 0.22 Å. Similar

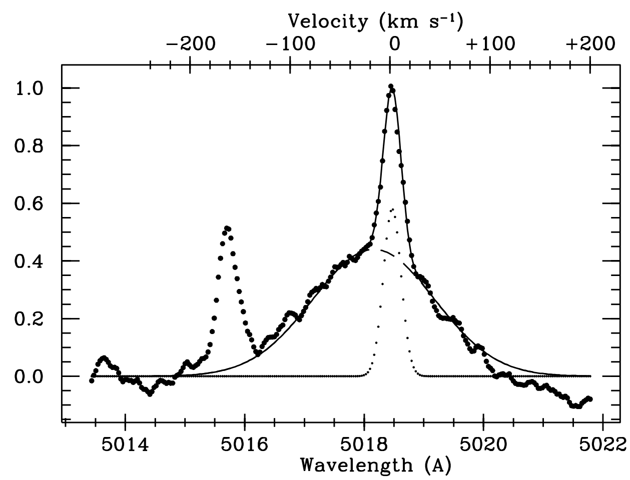

FIG. 3.—Fe II λ5018 line in EX Lup on 1998 June 23, decomposed into two Gaussians. The input data are represented by a series of heavy points, the Gaussians by lighter points and a dashed line, and the sum of the two Gaussians by a continuous solid line. The narrow Gaussian component is near the absorption-line velocity of the star, while the BC is shifted shortward with respect to it by 20 km s^{-1}. The isolated emission line on the left is He I λ5015.67.

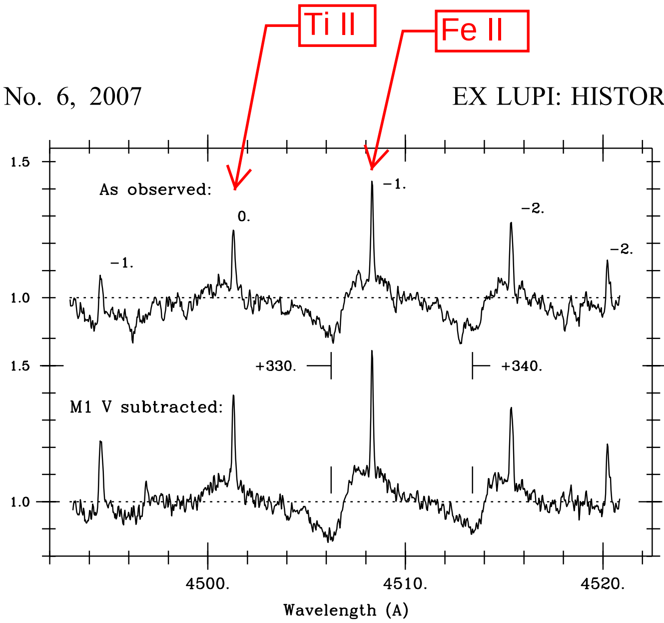

Fig. 4.—Same region as in Fig. 2 on 1998 June 23, before and after the spectrum of the M1 V star HD 147379 has been subtracted to remove the M-type absorption features in EX Lup. The velocities (in km s^{-1}) of a few features are indicated.

values are found from fits to other strong Fe II lines. The W value of the λ5018 line is about 3 times larger than those near 4500 Å, and its FWHM is also 3 times larger. Investigators of TTS spectra have suggested that the BC of the emission lines is formed by gas in the accretion funnel flow (Edwards 1997; Beristain et al. 1998; Najita et al. 2000). If so, the negative velocity shift of the BC (observed in EX Lup and in many TTSs) is puzzling; see the comments by Alencar et al. (2001). In the case of DR Tau, Symington et al. (2005) explain it as being produced by the infalling gas on the far side of the star, the near side being concealed by the disk.

Longward of many of the stronger Fe II and Ti II lines on the 1998 spectrum are broad, asymmetric "reverse P Cyg" absorption components with minima at +320 to +340 km s^{-1}. They can be seen more clearly if the spectrum of the M0 V star HD 147379 is subtracted from the 1998 exposure, after shifting it in wavelength and adjusting the scale to minimize the M-type absorption structure in the result. Figure 4 shows the result for the 4500 Å region if the M star contributed 0.15 of the total flux to that of EX Lup.

These displaced absorptions provide clear evidence of infall. They were no longer present at the ionized metal lines following the 1998 maximum. Information is limited for the Balmer lines, but they seem to behave in the same way. Unfortunately, only the longward edge of Hα fell within the edge of that order on the 1998 exposures, but it was enough to show that no longward absorption component was present at that time, nor was any such feature seen on the later HIRES exposures, where the entire line could be examined. In fact, except for some very minor structure near the line center, and a small change in the slope of the shortward wing at about −60 km s^{-1}, the Hα emission line was symmetric and essentially structureless in 2000–2004, very much as the profile published by Reipurth et al. (1996), which was obtained about 10 days after the 1994 March maximum. This lack of a reversed P Cyg absorption at Hα is familiar from other TTSs. However, in 1998 Hβ was flanked longward by an absorption component at +340 km s^{-1} that had disappeared by 2002. The same feature was seen at Hβ and the higher Balmer lines during the 1994 maximum by Lehmann et al. (1995).

During the 2.6 hr over which the 1998 spectrograms were obtained, there were small variations, at about the 5% level, in the central intensities and widths of the stronger emission lines, but no systematic change was apparent.

2.2. *The Postoutburst Spectrum*

Figure 2 shows that the W values of the prominent emission lines were 2.5–3.0 larger in 2000–2004 than in 1998, even though their BCs had essentially vanished. Such an increase in W is expected on account of the fading of the continuum, although one would need precise photometry to be sure this is the complete explanation.

In 2002, the first spectrum following the outburst, one also sees in Figure 2 that those emission lines were wider than in the succeeding exposures: FWHM = 11 km s^{-1} in 2002 versus 6–8 km s^{-1} in 2003–2004 (following correction for instrumental resolution), although the W values remained about the same. There was also a concurrent change in the Hα/Hβ ratio in those years (the equivalent widths of the Hα and Hβ emission lines are given in Table 1).

The longward absorption component at Hβ was absent on the postoutburst spectra of EX Lup, and the BCs of the stronger ionized metal emission lines were absent or marginally present. The NCs were present on all the postoutburst spectra. They remained at the same (heliocentric) velocity of -1 ± 0.4 km s^{-1}, but the helium emission lines were consistently shifted longward: the mean He I line velocity was $+2.1 \pm 0.4$ km s^{-1}, and He II λ4685 was at $+9.0 \pm 1.2$ km s^{-1}.

The lines of the M-type spectrum are only slightly broader than those in the M1 V standard HD 147379; the two match very well if the standard is spun up by an additional 3 km s^{-1}. The velocity of the absorption spectrum, the average of 10–12 reasonably unblended lines, is given for each date in Table 1; the zero points were checked by measures of atmospheric lines. Their mean remained constant at $+0.2 \pm 0.1$ km s^{-1}. There is thus no indication that the star is a spectroscopic binary. The agreement in emission- and absorption-line velocities shows that, as in TTSs, the NC originates near the stellar surface.

The absorption lines of the M-type spectrum in Figure 2 became deeper as the star faded. This can be quantified as follows. If the spectrum is assumed to be the combination of an early M dwarf and a featureless continuum, then r, the ratio of the two fluxes, can be obtained by ratioing the W values (or the line depths) of the absorption lines in the reference star with those in the combination,

$$r = \frac{W(\mathrm{ref})}{W(\mathrm{EX\ Lup})} - 1,$$

where W here is the sum of all lines in regions free of obvious emission, although incipient emission in line cores will exaggerate the effect. Table 2 shows the average results for three regions (4750, 5550, and 6150 Å) on all the HIRES spectrograms, the reference star being HD 147379. No significant difference is seen if the reference is instead taken to be BD +10 3724. The internal standard deviation of these ratios, inferred from the scatter of subsamplings across the ∼30 Å windows, is also given.

One, and perhaps two, trends can be seen in the data of Table 2. First, the general increase of the r-values toward shorter wavelengths has also been observed in a number of active TTSs (Basri & Batalha 1990; Hartigan et al. 1991; Edwards et al. 1994) and arises because the veiling continuum is hotter than the M-type reference. Second, the general falloff of r down Table 2, if real, could be understood if the veiling level slowly declines following the most recent flare-up, as can be seen from the times (in

TABLE 2

VEILING

DATE (UT)	FLUX RATIO 4750 Å	5550 Å	6150 Å	ΔT[a]
1998 Jun..................	5.9 ± 0.4	2.9 ± 0.2	3.3 ± 0.1:	−10
2000 Feb	2.4 ± 0.2	1.3 ± 0.1	0.9 ± 0.1	+206
2003 Jul...................	2.2 ± 0.2	1.0 ± 0.2	1.0 ± 0.2	+326
2004 Jun..................	1.2 ± 0.1	0.8 ± 0.1	0.9 ± 0.1	+669

[a] Approximate number of days since the previous (or concurrent) maximum.

days) since the previous maximum, given in the last column of Table 2 for each observation.

The question then arises: can the photometric flare-ups of EX Lup be simply a consequence of the appearance of the hot continuum? The V-magnitude response to an additional contribution is $\Delta V = 2.5 \log(1 + r_{5550})$. The minimum value of r_{5550} is about 0.8 ± 0.1, increasing to 2.9 ± 0.2 at outburst, so a V brightening of 0.84 ± 0.08 mag would be expected. But the observed value is 1.6 mag (from about 12.9 to 11.3). Thus, the addition of the veiling continuum *alone* cannot account for the amplitude of the 1998 flare-up. The two could be reconciled if, during the flare-up, in addition to the contribution of the hot continuum, that of the M star increased by a factor of about 2.

3. DISCUSSION

EX Lup is located at the edge of a gap in the Lupus cloud complex between Lupus 3 and 4 (Cambrésy 1999). Its optical radial velocity agrees with the CO velocity near its position, also about 0 km s^{-1}, judging from the tabulations of Murphy et al. (1986) and Tachihara et al. (2001). So there is no reason to doubt that the star, although it lies in that gap, is associated with those clouds. Furthermore, over the 6 yr of the HIRES observations there is no evidence of binary motion. The only indications that the 1998 flare-up had any lingering effect on the underlying star were the changes described in § 2.2.

When EX Lup undergoes a major outburst, the spectroscopic consequences are seen as the appearance of a hot continuum that partially submerges the M-type absorption spectrum, of BC emission-line structure, and of reversed P Cyg absorption features. Some activity is present at a low level even when the star is near minimum, because it is always bluer than expected for a normal M0 V star. Near minimum, at $V \approx 13.2$, Bastian & Mundt (1979) found that $B - V$ ranged between 0.85 and 1.20, as compared with the intrinsic $B - V = 1.41$ of an M0 V star. The gas that produces the reversed P Cyg structure seen at the time of outburst presumably comes from the circumstellar material responsible for the infrared excess reported by Gras-Velázquez & Ray (2005). The silicate features at 10 and 20 μm detected with *Spitzer* (Kessler-Silacci et al. 2006) probably originate in the same material, but no gaseous CO was detected at the position of EX Lup by van Kempen et al. (2007). There is no evidence for the presence of a close optical or spectroscopic companion that might otherwise be the source of the infall. The puzzling lack of evidence for reddening in the optical region could be a consequence of aspect: we may be observing the star from high above the disk plane, although that conflicts with the interpretation (Symington et al. 2005) of the shortward shift of the BC as being due to occultation of the near-side inflow by the inner edge of the disk.

The hot emission-line spectrum that appears in EX Lup at outburst is a mild version of that seen in DR Tau, a very active

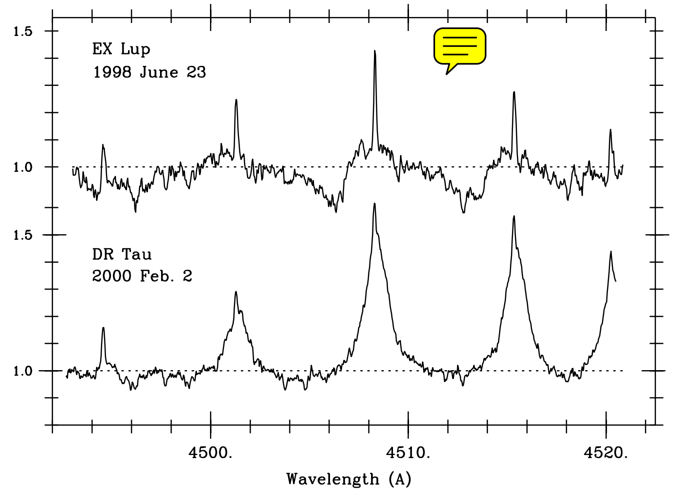

FIG. 5.—Comparison of the 4500 Å region of EX Lup on 1998 June 23 (*top*, from Fig. 4) with the same region in the very active TTS DR Tau (*bottom*); the lower spectrum has been shifted slightly in wavelength to match the upper. In DR Tau at this time the BCs were shifted longward with respect to the NCs, and so caused the minor discontinuities present longward of the emission-line peaks. On this occasion, the reversed P Cyg absorptions that have sometimes been prominent in DR Tau were absent.

TTS that has received much spectroscopic attention (see Beristain et al. 1998 and references therein). There is a similarity between the two in the sense that both are of type M0 and of low $v_{eq} \sin i$ (Basri & Batalha 1990), but the level of activity in DR Tau during the past 3 decades has been much higher.[3] Figure 5 shows the 4500 Å region in both stars. The gross difference in emission-line profiles is because the BCs in DR Tau at that time were much stronger than those in EX Lup, in the case of Fe II λ5018 by a factor of about 3.5. For that same line, the ratio of BC to NC equivalent widths was 5 in EX Lup (in 1998) and 22 in DR Tau.

4. FINAL REMARKS

It remains to be seen whether the behavior of EX Lup, as described here, can serve as a template for a distinct class of pre-main-sequence stars. That question may be clarified by an ongoing investigation of several other EXors for which HIRES spectroscopy has now been obtained. A larger issue is whether the behavior of EX Lup is understandable in terms of the leftward migration of low-mass TTSs across the Hertzsprung-Russell diagram. For example, one might speculate that as DR Tau ages it may relax to its pre-1960 brightness and, as its disk decays, will exhibit only sporadic flare-ups as exhibited by EX Lup today, before becoming quiescent altogether. Some encouragement for this idea that EX Lup is indeed an older object might be seen in its location almost in the clear, well away from the major seat of star formation in the Lupus clouds. But this is weak evidence: some active TTSs are located outside the boundaries of their parent clouds; see Herbig (2005) for recently recognized examples. Nor is the implication that weak-lined TTSs should be

[3] Only scattered photographic observations are available for DR Tau prior to about 1960. They range between about 13.5 and 15.0, but several single observations found the star much brighter, at 11.5–12.4 (see the light curve in Herbig 1989). Little is known of its spectrum at that time. A slow brightening superposed on rapid fluctuations began about 1961. CCD photometry between 1975 and 1998 shows that the star continued to vary rapidly between about $B = 11.2$ and 14.0, frequently from night to night.

older than CTTSs borne out by observation: in young clusters, at least, the average age is essentially the same.

So these issues remain unresolved. It is possible that the larger picture is only confused by observational minutiae such as those detailed in this paper. Certainly, the issue deserves more critical observations or deeper insight.

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